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Leading edge erosion of wind turbines: effect of solid airborne particles and rain on operational wind farms

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Abstract

Leading edge erosion (LEE) affects almost all wind turbines, reducing their annual energy production and lifetime profitability. This study presents results of an investigation into eighteen operational wind farms to assess the validity of the current literature consensus surrounding LEE. Much of the historical research focusses on rain erosion, implying that this is the predominant causal factor. However, this study showed that the impact of excessive airborne particles from seawater aerosols or from adverse local environments such as nearby quarries greatly increases the levels of LEE. Current testing of leading edge protection coatings or tapes is based on a rain erosion resistivity test, which does little to prove its ability to withstand solid particle erosion and may drive coating design in the wrong direction. Furthermore, it was shown that there is little correlation between test results and actual field performance. A method of monitoring the expected level of erosion on an operational wind turbine due to rain erosion is also presented. Finally, the energy losses associated with leading edge erosion on an operational wind farm are examined, with the average annual energy production dropping by 1.8% due to medium levels of erosion, with the worst affected turbine experiencing losses of 4.9%.

Keywords

wind turbines; erosion; performance; aerodynamics

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1. Introduction

Leading Edge Erosion (LEE) describes the phenomena of the erosion of a wind turbine blade's leading edge by rain, hail, UV, sand, dust, insects and other airborne particulates. This erosion has a deleterious effect on the blade's aerodynamic efficiency, reducing the turbine's Annual Energy Production (AEP) and hence lifetime profitability. Almost all wind turbines will be affected by LEE due to the ubiquity of its causal factors. EDP Renewables inspected 201 rotor blades on a wind farm after fourteen years of operation and discovered that 174 blades (87%) had visible signs of erosion, with 100 blades (50%) showing severe levels of LEE¹. It is clear from the growing amount of research publications and industry articles that LEE is garnering an increasing amount of economic impetus due to four major trends: the rapid growth of installed wind turbine capacity; the increase in turbine power ratings; the extension of turbine service lives; and the decline of subsidies forcing a profitability maximisation effort. However, it is also evident from the available literature that the industry's approach to this issue is still very much in its infancy considering the associated financial impact.

The application of leading edge protection (LEP), namely coatings and tapes, is the proactive solution to minimising the effect of LEE. Coatings are typically applied after the blade has been manufactured whereas tapes are mainly used for field repair. This is because the application of a tape results in increased drag due to early flow transition at the backward step of the tape, which can result in an AEP loss of up to 2%²⁻³. The current industry testing standard for these coatings and tapes is based on an accelerated rain erosion weathering technique, where the coating or tape is applied to a test subject on a whirling arm that rotates at approximately 140 m/s in an imposed artificial rainfall. This testing methodology was adopted from the aircraft industry⁴, with a wind specific standard yet to be developed. There are two main shortfalls of this being the sole testing method for LEP coatings and tapes. The first is that it relies on the assumption that rainfall is the predominant causal factor of LEE, as it fails to account for solid particle erosion. However, it has been shown that the erosion effect of hail is much more severe due to the greater particle mass⁵⁻⁶ and this can also be extrapolated to the presence of any airborne solid particulates such as seawater aerosols or dust emitted from quarries. The second is that it is currently unknown whether the accelerated weathering technique (developed for high velocity helicopter rotors) results in different physical fatigue mechanisms occurring, which would nullify test results being an accurate prediction of actual

field performance. The overarching concern with an inappropriate testing methodology is that it may drive future LEP design in the wrong direction.

The monitoring of blade health is vital to maximising service life and minimising AEP losses due to LEE and other surface deficiencies. Typically, these blade inspections are carried out either by visual inspection from the ground using telescopic lenses or by ropes access teams manually scaling the blade. Drone inspections are becoming increasingly common as, while they are a similar cost per turbine inspection, they are much quicker and can help reduce turbine downtime. Blade Condition Monitoring Systems are garnering attention due to their ability to flag damage without incurring high inspection costs and long periods of turbine downtime. The most popular method involves the installation of accelerometers in the blades to correlate Eigenfrequency deviations to mass losses. Strain gauges are often used in conjunction. However, the technology is still unable to address all failure modes, particularly LEE, due to their associated error tolerances. This begs the question of whether a dynamic modelling approach could be developed to estimate the extent of LEE that has occurred and hence correlate this to an AEP loss to optimise repair logistics.

In an era of declining subsidies for wind energy, the ability to accurately estimate the impact of LEE on AEP over a turbine's lifetime is vital to enable developers to prove the commercial viability of a project. Historical research has focussed on using CFD and/or wind tunnel testing to estimate the associated losses. The majority of these studies indicate a general literature consensus of AEP losses of up to 5%⁷⁻⁹. However, one study suggests that it could be as high as 25%¹⁰. This variance substantiates the need for AEP loss analysis to be run on operational turbines so as to better quantify the financial impact of LEE.

There are four main objectives to this study. The first objective is to examine different operational wind turbine sites which are subject to a variety of environmental conditions to assess the validity of current LEE aetiology. The second objective is to investigate proof of concept of a novel method of monitoring the expected levels of LEE on a wind turbine blade using rainfall data. Such a system has the potential to greatly assist maintenance and elongation of wind turbine blade service life by optimising repair logistics and costs whilst also striving to minimise the energy losses associated with eroded blades. The third objective is to analyse the validity of current testing standards for leading edge protective coatings and tapes, by comparing test results to actual field results. The final objective is to quantify the AEP losses associated with LEE using operational turbine data. This serves to provide a greater understanding of the associated AEP losses and to ascertain the validity of the previous research papers mentioned above. It also provides the basis upon which estimates of the annual economic impact of LEE to the UK wind energy industry can be calculated.

2. Methodology

This study was very fortunate in having access to Senvion's operational data for wind farms across the UK. The main data points used were the hourly average rotational velocity of the blades and the associated blade quality inspection reports after two years of operation. Average hourly rainfall rates were provided by the Met Office, collected from the nearest rain gauge to each wind farm.




2.1 Sample Size Selection

The first objective of this study was to assess the validity of current LEE aetiology by examining different operational wind farms that were subject to different environmental conditions. Observations were collected from a sample size of eighteen wind farms across the UK, consisting of four subsamples based on a particular erosive factor of interest. Seven windfarms were chosen where the average annual rainfall amounts varied from 626mm to 1185mm. The average annual days of hail was less than ten for all of these sites and they were far from the sea or any other feature that would produce excessive airborne particles. These sites were used to examine the effect of varying levels of rainfall. Two sites were chosen in the North of Scotland where the average annual days of hail was 25 to examine the erosive effect of hail. The sites were far enough from the sea or any other feature that would produce excessive airborne particles. For examining the erosive effect of seawater aerosols, two sites were chosen on the East coast of Scotland, less than 2km from the sea. Finally, seven sites were chosen that had quarries within 5km. This was to examine the erosive effect of excessive airborne particulates. They were far from the sea and levels of hailfall were constant.

All the turbine blades were inspected after approximately two years of operation by a ropes access team. These inspection reports allowed the severity of LEE experienced by each turbine blade to be graded. The grading system

developed was relatively coarse as the inspection reports were not always concise and were often carried out by different third parties, resulting in a lack of consistency. This grading system is outlined in Table 1. Each blade was graded based on the worst erosion seen. For example, if a blade had both light and medium erosion, the blade would be graded as a 2. The average of the grades of the three blades was computed for each turbine and then this was averaged for all the turbines in the wind farm to give the final wind farm Erosion Grade.

Table 1: Erosion grading system

Erosion Grade = 0	Erosion Grade = 1
No visible erosion, coating still in good condition	Small areas of erosion, visible signs of damaged coating
	
Erosion Grade = 2	Erosion Grade = 3
Larger areas of erosion, coating clearly eroded in long patches	Wider areas of erosion, coating completely eroded and laminate clearly exposed
	

2.2 Dynamic Modelling Approach

The second objective of this study was to assess whether it was possible to predict the onset and severity of LEE using a dynamic modelling approach based on available operational data. The data available was hourly rainfall rates for each wind farm and average hourly blade tip speeds for the wind turbines. This allowed the following Erosion Severity Indicators (ESI) to be computed for each wind turbine.

A. ESI 1: Cumulative Impact Energy

The impact energy of a particle colliding with a rotating wind turbine blade can be calculated using the Kinetic Energy equation:

$$KE = \frac{1}{2}MV^2 \quad (1)$$

(where M is the mass of the particle and V is the impact velocity)

The mass of the raindrop can be approximated using Best's approximation of the predominant raindrop diameter¹¹ and assuming a water density of 1000 kg/m³:

$$D_p = 1.0011I^{0.232} \quad (2)$$

(where D_p is the predominant raindrop diameter and I is the rainfall rate in mm/hr)

The terminal velocity of the raindrop, V_t , can be calculated using Atlas's approximation¹²:

$$V_t = 9.65 - 10.3e^{-0.6D_p} \quad (3)$$

Using vector analysis, the rain impact velocity on a rotating blade tip can be analysed as shown in Figure 1:

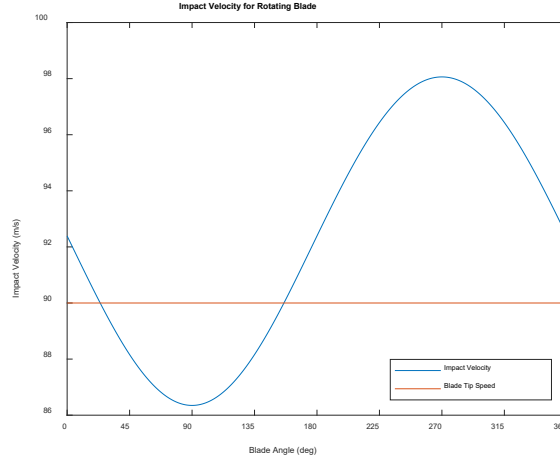


Figure 1: The variation in rain impact velocity for a rotating blade tip using vector analysis (where the angle of 0° corresponds to the blade pointing upwards), assuming a 2mm raindrop entrained in 20m/s wind and a tip speed at a max of 90m/s

This shows that the tip speed is a reasonable approximation for the raindrop impact velocity at the blade tip. Accordingly, the impact energy of a raindrop colliding with a rotating wind turbine blade tip in a given rainfall rate can be calculated. Therefore, periods of high precipitation intensity and high blade tip speeds will result in greater impact energies as shown in Figure 2:

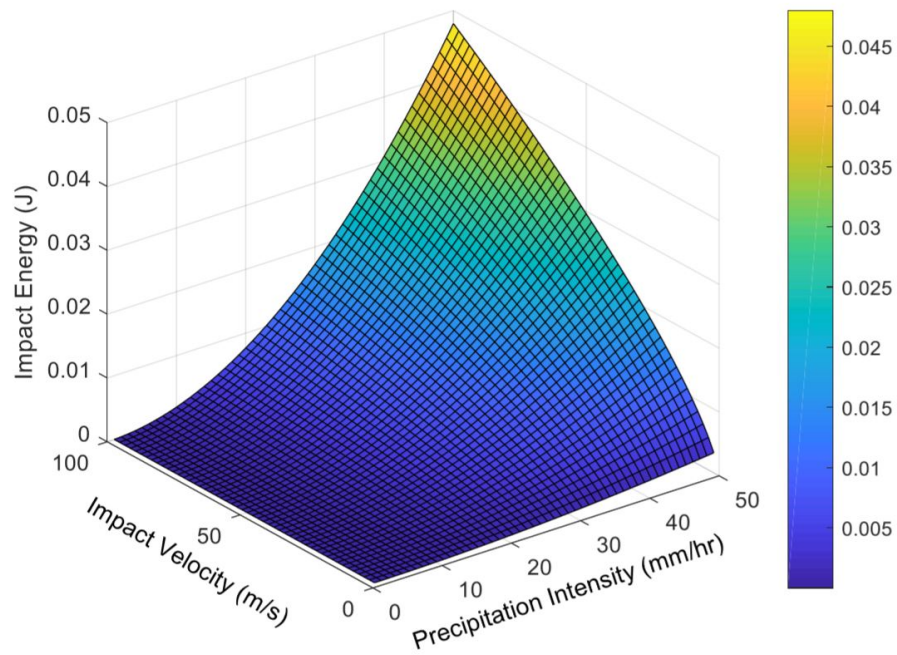


Figure 2: Raindrop impact energies as a function of impact velocity and rainfall rate

To approximate the cumulative impact energy that a unit area of the blade would be exposed to over a given time period, Springer¹³ gives the number of droplets impinging upon a unit area to be:

$$n = \frac{6 V \cos \theta}{\pi V_t D_p^3} I t \quad (4)$$

(where θ is the impact angle and t is the time in seconds)

Therefore, by combining Equations 1-4 and assuming an orthogonal impact angle, the cumulative impact energy per unit area per hour can be computed as a function of the blade tip speed and rainfall rate and then summed over the turbine's lifetime.

B. ESI 2: Cumulative Impact Force

The impact force imparted through liquid droplet impingement is another indicator of the impact magnitude¹⁴⁻¹⁵:

$$F = \frac{M V^2}{D_p} \quad (5)$$

Combining this with Eq. 4, the cumulative impact force per unit area per hour can be calculated and then summed over the turbine's lifetime.

C. ESI 3: Water-hammer Pressure

The modified water-hammer pressure equation, proposed by Dear and Field¹⁶, provides an accurate method of approximating the stresses induced during liquid droplet impingement⁵:

$$P = V \frac{\rho_l c_l \rho_c c_c}{\rho_l c_l + \rho_c c_c} \quad (6)$$

(where ρ_l , ρ_c , c_l and c_l are the densities and speed of sound of the liquid and coating respectively)

Combining this with Eq. 4, the stress induced per unit area per hour can be approximated and again summed for the blade's spinning lifetime.

ESI 4: Average Rain Erosion Stress per Unit Area per Hour

Springer¹³ provides a method of accounting for the average stress on the coating surface, σ_{avg} , due to stress wave patterns between the liquid droplet, coating and interface. This can be represented as:

$$\sigma_{avg} = P \frac{1 + \varphi_{sc}}{1 - \varphi_{sc} \varphi_{lc}} \left[1 - \varphi_{sc} \frac{1 + \varphi_{lc}}{1 + \varphi_{sc}} \frac{1 - e^{-\gamma}}{\gamma} \right] \quad (7)$$

(where φ_{sc} and φ_{lc} represent the acoustic impedance ratios between the substrate and coating and liquid and coating respectively, and γ is a parameter relating to the coating thickness)

Combining this with Eq. 4, the average stress due to rain erosion per unit area per hour can be computed and summed over the blade spinning lifetime.

2.3 Comparing Test Results to Operational Performance

There are two main stages to liquid droplet impingement on a ductile surface¹⁷⁻¹⁸. The first is the compressible stage, where the water-hammer pressure is produced, which is responsible for most of the stress damage resulting from liquid droplet impact. The second is the incompressible stage, where the pressure approaches the static pressure and a laterally jetting mechanism occurs. The velocity of this lateral jet has been measured to be up to ten times the original impact velocity of the water droplet¹⁶. It is this mechanism that is responsible for the material removal. The overall erosion timeline due to liquid droplet impingement is depicted in Figure 3:

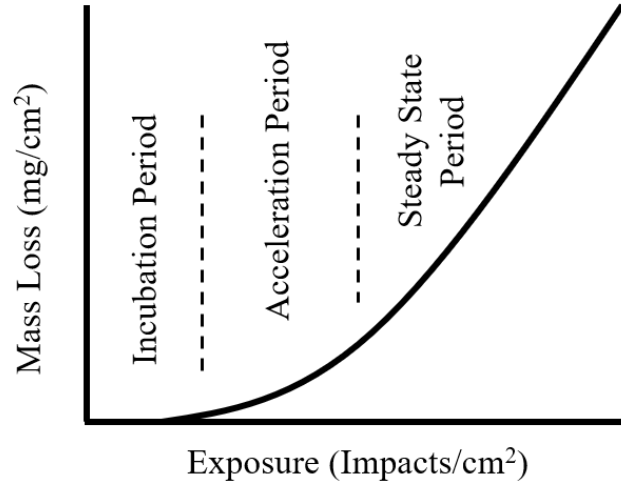


Figure 3: Erosion timeline for liquid droplet impingement

This shows that there is an initial period where no mass loss occurs called the incubation period. This incubation period consists of crater formation (governed by the compressible stage) until lateral jetting starts to abrade the crater walls (governed by the incompressible stage) at which point material loss commences and the erosion rate increases¹⁹⁻²⁰. Therefore, a dynamical modelling system for LEE must be able to approximate the stage at which the incubation period has been breached and hence the onset of erosion has commenced.

Springer developed a model to estimate the number of droplets that could occur before the end of the incubation period using a modification of the Miner fatigue rule¹³. This considers not only the coating properties but also how the coating performed in a rain erosion test. This data was made available by the OEM and thus also acted to test the validity of the standard rain erosion testing methodology. The approach is summarised below:

1. An approximate value of the “effective strength parameter”, S_{ec} , is obtained by examining the length of the incubation period, t_{ic} , experienced in an accelerated rain erosion test:

$$S_{ec} = \left(\frac{It_{ic}V\sigma_{avg}^{5.7} \cos(\theta)}{0.0168D_pV_t} \right)^{\frac{1}{5.7}} \quad (8)$$

2. For each hour of rainfall experienced by the turbine, calculate n , the number of impacts per unit area, given by Eq. (4).
3. Springer then gives a method of calculating the number of impacts before the end of the incubation period, n_{ic} , as:

$$n_{ic} = \frac{8.9}{d^2} \left(\frac{S_{ec}}{\sigma_{avg}} \right)^{5.7} \quad (9)$$

4. For each hour, a value of $\frac{n}{n_{ic}}$ can be obtained. From the Miner rule, failure occurs after different fatigue loadings when:

$$\frac{n_1}{n_{ic1}} + \frac{n_2}{n_{ic2}} + \frac{n_3}{n_{ic3}} \dots = 1 \quad (10)$$

Therefore, the onset of erosion can be approximated when the cumulative sum of $\frac{n}{n_{ic}}$ reaches 1.

2.4 Assessing Annual Energy Production Losses due to LEE

The fourth and final objective of this project was to analyse the energy losses on commercial wind turbines due to LEE. Evidently it is not possible to simply compare the monthly or annual energy production of the turbine as this will vary with monthly and annual fluctuations in wind conditions. Therefore, the methodology used was Power Curve Performance Testing, as a degradation in the turbine’s power curve is independent of wind conditions. Power curves were created by measuring the average power output produced by the turbine for each wind speed bin over an annual period. These reference wind speed bins were recorded from the site meteorological

mast as the nacelle anemometry is affected by turbulence induced by the spinning blades and hence is incapable of providing an accurate reference wind speed for power curve creation. An example of a resulting power curve is shown in Figure 4. These were then multiplied against the expected annual wind distribution of the site (Figure 5), which was procured from the Preliminary Wind and Site Assessment report of the wind farm. This gave a theoretical AEP value that was independent of the inter-annual variability in wind conditions. This AEP value could then be compared to previous years to identify any decrease in the power performance of the turbine due to LEE.

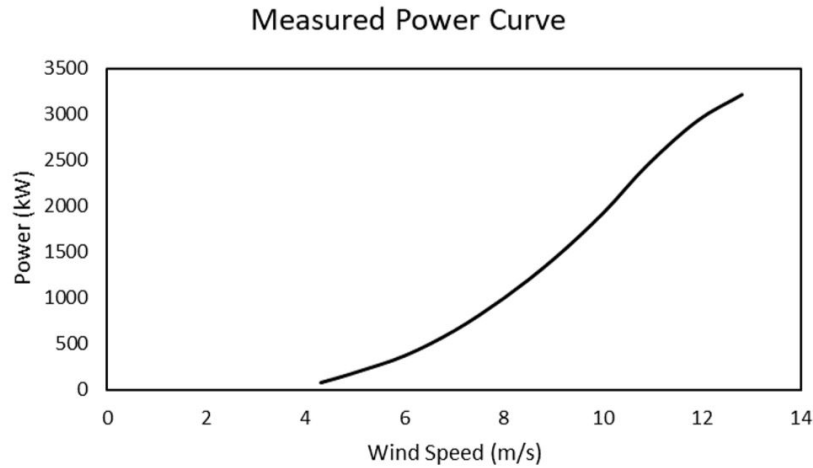


Figure 4: Example of a measured power curve, from 4-13m/s

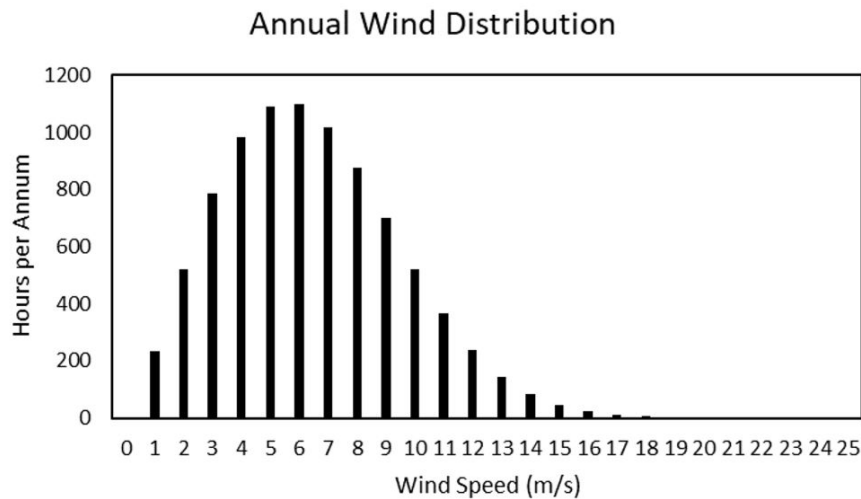


Figure 5: Expected annual wind distribution of studied site, from the pre-construction wind and site assessment report

3 Results and Discussion

3.1 Rain Erosion Sample Size

Figures 6 to 9 compare the Erosion Grade for the seven wind farms in the rain erosion risk population against the average ESI that was calculated for a turbine blade in that wind farm.

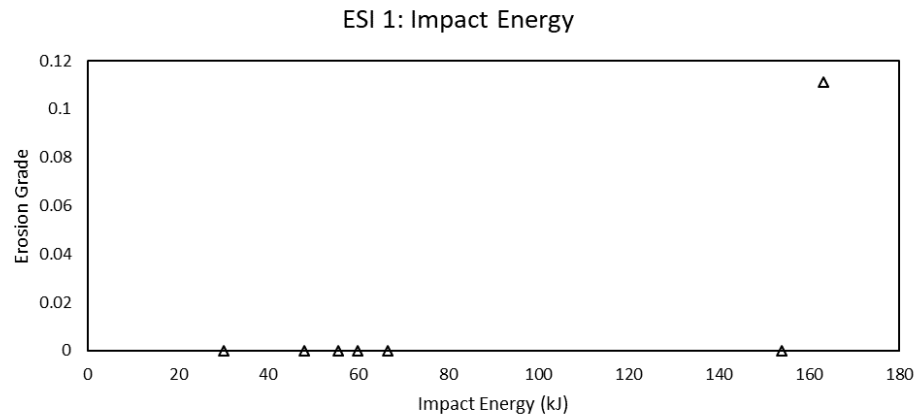


Figure 6: Erosion Grade vs the average cumulative impact energies in the rain erosion risk areas

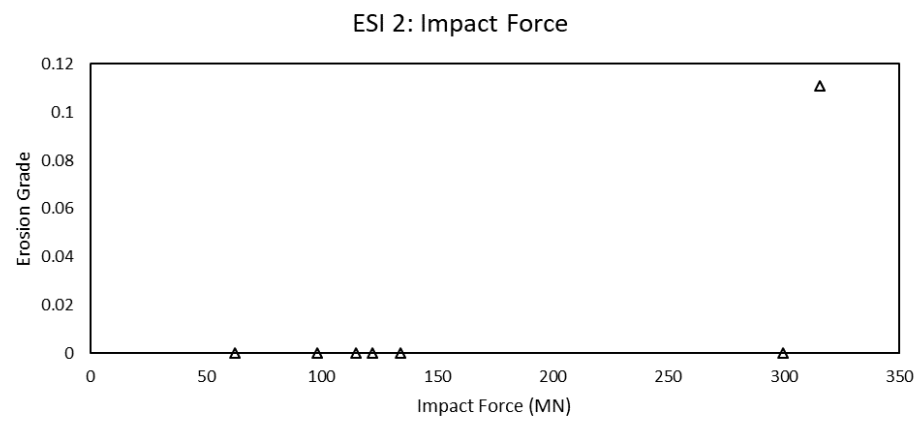


Figure 7: Erosion Grade vs the average cumulative impact force in the rain erosion risk areas

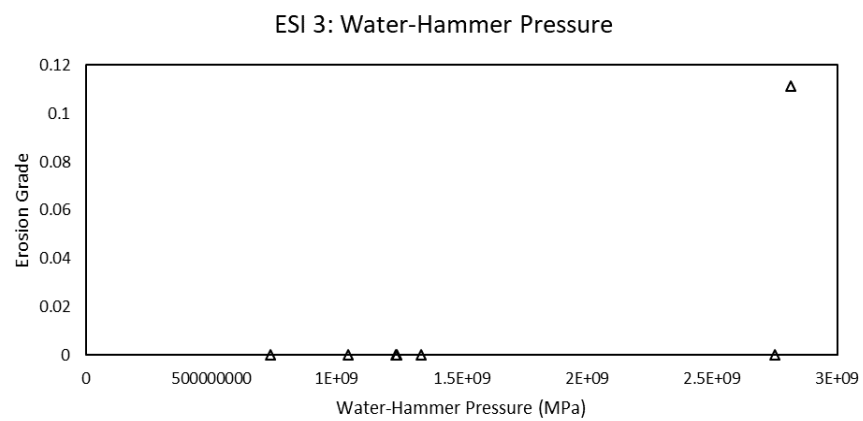


Figure 8: Erosion Grade vs the average cumulative water-hammer pressure in the rain erosion risk areas

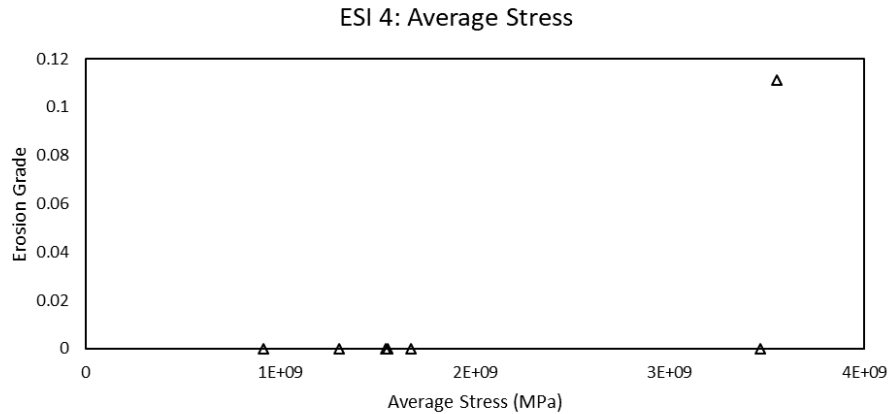


Figure 9: Erosion Grade vs the average cumulative average stress in the rain erosion risk areas

Figures 6-9 show that only one wind farm in the rain erosion risk population had visible signs of LEE and that the extent of this was very small. However, the potential of the dynamic modelling approach is validated in that the site with erosion possesses the highest levels of ESI's. The results correspond well with the rain erosion timeline theory as there is a clear incubation period where no erosion is experienced.

From Figure 6, it could be postulated that the onset of LEE and the end of the incubation period occur once the turbine has experienced cumulative impact energies greater than 160 kJ. This logic could similarly be applied to all the other ESI's. Evidently, this would likely be inaccurate as it is only based on one data point. Therefore, a greater sample size with testing periods longer than two years would need to be examined to verify with greater accuracy the point at which the incubation period ends and the onset of LEE begins. The cumulative ESI sum after this point could then give an indication of the erosion severity.

3.2 Comparing Test Results to Operational Performance

Figure 10 looks at the performance of the Springer model in correlating test results to actual operational performance:

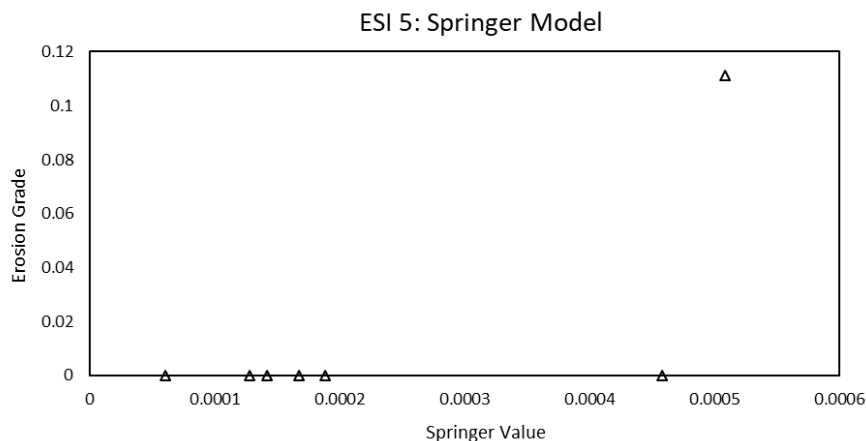


Figure 10: Erosion Grade vs the average cumulative Springer result

The result of the Springer approach for the one site with erosion was 0.0005 but according to the Miner rule, failure should theoretically occur when this value reaches 1. This may be due to the limitations of the Miner rule, particularly its linearity and inability to account for varying sequences of stress cycles²⁰. This limitation is acceptable for rain erosion testing, where the rainfall rate is constant throughout, but becomes more detrimental in actual turbine analysis, due to greater variability in stress cycles. However, Figure 10 also shows that there seems to be little correlation between test results and actual operational performance, most likely due to different physical mechanisms occurring when a sample is exposed to severe rainfall erosion continuously in an accelerated test in comparison to much lighter rainfall erosion in varying cycles in operational conditions.

3.3 Hail, Seawater Aerosols and Other Airborne Particles

Figures 11-14 compare the Erosion Grade for all the wind farms in the different risk populations against the average ESI for a turbine within that wind farm.

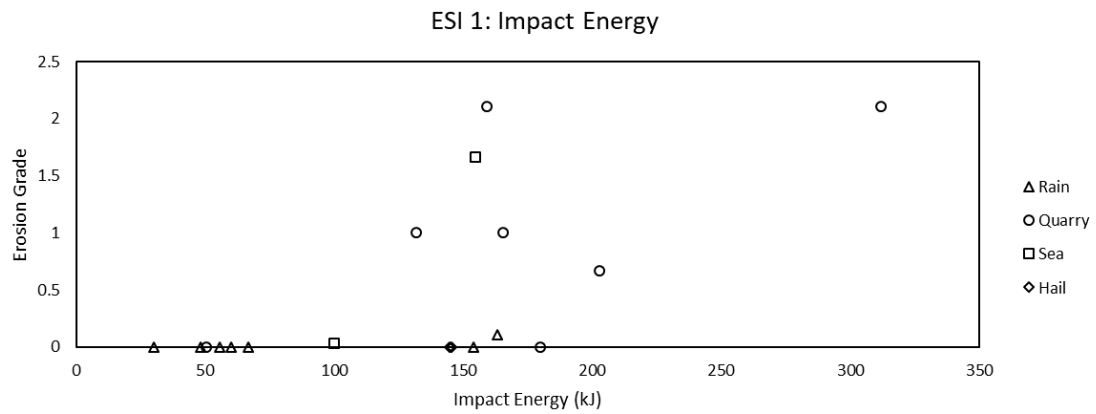


Figure 11: Erosion Grade vs the average cumulative impact energies for wind farms in different risk population

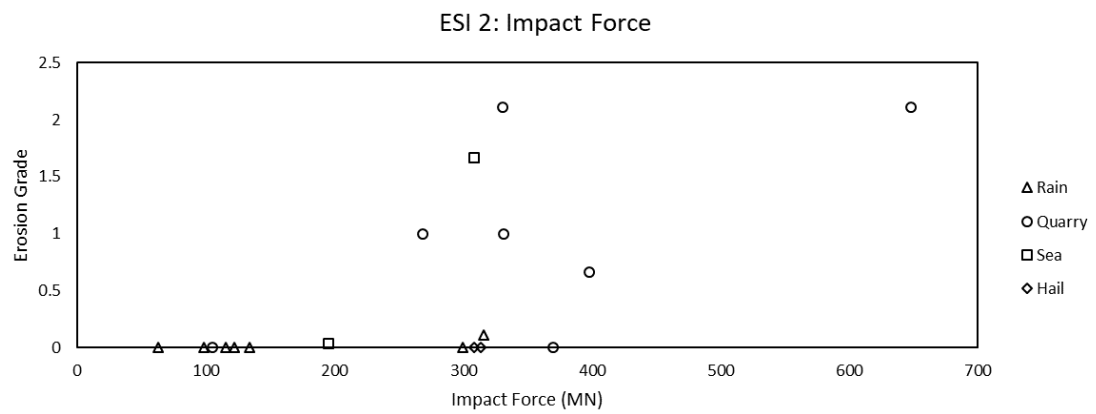


Figure 12: Erosion Grade vs the average cumulative impact force for wind farms in different risk population

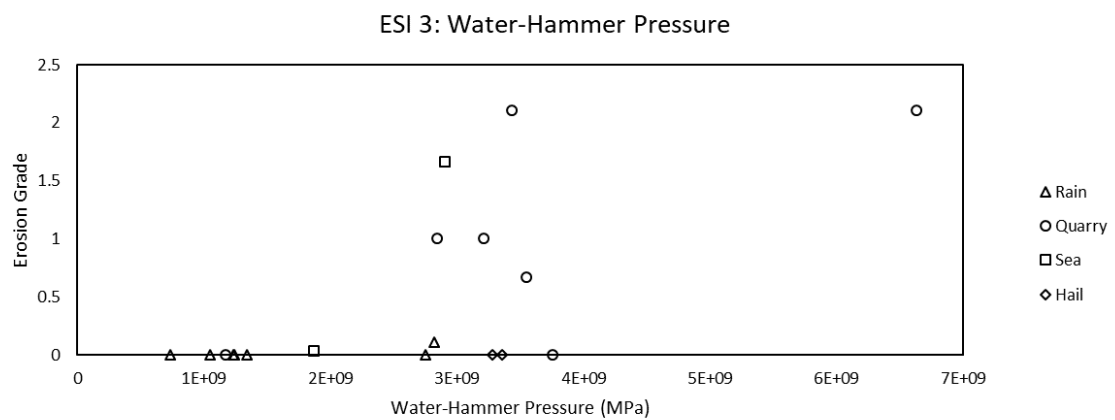


Figure 13: Erosion Grade vs the average cumulative water-hammer pressure for wind farms in different risk population

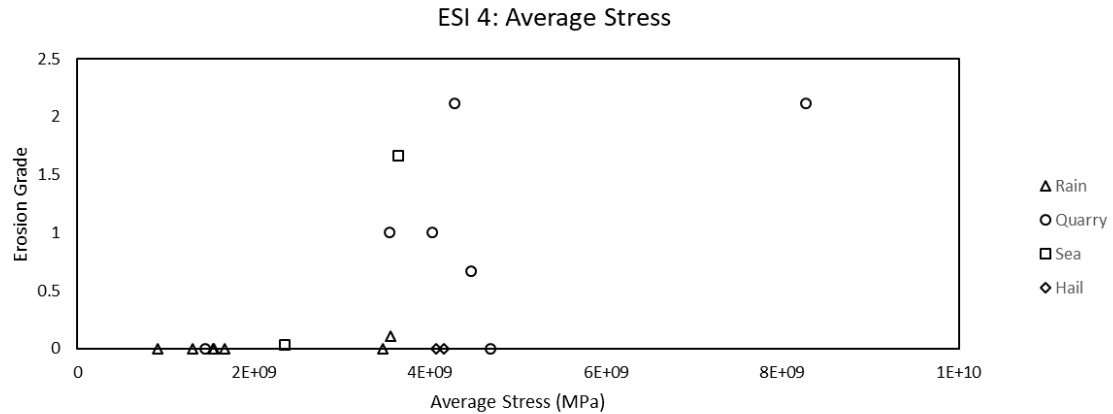


Figure 14: Erosion Grade vs the average cumulative average stress for wind farms in different risk population

The Erosion Grade is clearly considerably higher for sites that are subject to the presence of excessive airborne particles from quarries or sea-salt aerosols. The ESI's only account for rain erosion and hence this higher Erosion Grade must be caused by additional exogenous factors i.e. sea-salt aerosols or dust emitted from quarries. Perhaps the most alarming result is the extent to which the presence of a quarry accentuates LEE. The Erosion Grade of the one wind farm that had LEE in the rain risk population was 0.17. Within a similar range of ESI's, the quarry sites have an Erosion Grade in the region of 1-2 due to the additional erosion effect imposed by excessive airborne particles. While the ESI's are somewhat temporally correlated (higher ESI's may represent longer operational times), there is no clear correlation between the Erosion Grade of the quarry risk population and the ESI's. This is likely due to different quarries emitting different levels of airborne particulates based on their distance, level of activity, direction from the farm and type. Interestingly, there still seems to be an incubation period, with two quarry sites showing no signs of LEE at lower ESI's.

It is also evident that sea-salt aerosols accentuate LEE. Site 11 had an Erosion Grade of 1.67. The site was within 50 m of the sea and was therefore the most representative example of an offshore turbine within the sample size. The comparatively high erosion grade substantiates the consensus that offshore turbines will experience greater erosion levels than onshore turbines²²⁻²³, particularly as this site was only affected by aerosols from the East. This is important from an economic perspective, with the average size of an installed offshore turbine in Europe in 2017 being 5.9 MW²⁴. An AEP loss of just 1% for this size of turbine with a capacity factor of 40% would result in an annual profitability loss of approximately £10,000.

Neither of the two farms within the hail sample size showed any sign of LEE, despite relatively high ESI levels. This is surprising in that these sites were supposed to receive approximately fifteen extra days of hail a year. This means that either these sites actually received relatively similar amounts of hail precipitation or that the length of the incubation period may in fact be longer and that the site within the rain erosion sample size that showed LEE might be an anomaly. Further exploration of this would require conducting inspections after a period longer than two years and the installation of hail precipitation sensors.

3.4 AEP Loss Analysis

The site that was analysed for AEP losses had an Erosion Grade of 2.11, which was the highest erosion level seen of all the sites in the sample size. The average AEP for all the wind turbines, calculated using the actual power curves and expected annual wind distribution, was 1.75% lower in the third year of operation in comparison to the first. Furthermore, the wind turbine with the worst erosion levels (Turbine 3) had an AEP loss of 4.93% between the first and the third year. The severity of these losses is reasonably aligned with the current literature consensus.

The LEE was repaired after three years and therefore, the fourth year of operation was analysed to assess whether there was a noticeable improvement in the power curve performance. Interestingly, the average AEP of the turbines decreased by an additional 1.29% after the repair. The repair coating that was applied had a recommended dry film thickness of 0.6 mm. It has been shown that a repair tape 0.2 mm thick has the potential to reduce AEP by up to 2% depending on the placement of the tape²¹. Therefore, it may be reasonable to infer that the thick repair

coating applied to these blades may have decreased the aerodynamic efficiency and AEP output. However, had the blade not been repaired, it is likely that losses would have been considerably worse considering the extent of LEE that was present. It is reasonable to assume that there may well be other minor mechanical degradations that lead to a decreased performance. Further testing across a great sample size is needed to produce more conclusive results. However, it does substantiate the current consensus that LEE can produce losses of 1-5%.

Finally, the economic impact of LEE was estimated on the understanding that losses would temporally degrade in the range of 1-5%. The GOV.UK Renewable Energy Planning Database was used to find the installed capacity and years of operation for every wind farm in the UK. Coupling this with the parameters shown in Table 2, the financial impact of LEE in 2019 was calculated to be £76.5 million.

Table 2: Parameters for estimating the economic impact of LEE in the UK

Parameter	Value
Onshore Capacity Factor	30%
Offshore Capacity Factor	40%
Assumed Energy Price	£70MW/hr
AEP Loss After Two Years	1%
AEP Loss After Five Years	2%
AEP Loss After Ten Years	3%
AEP Loss After Fifteen Years	5%

4 Conclusion

Analysis of the sites that were subjected to excessive airborne particles from quarries or sea-salt aerosols revealed vastly more severe levels of LEE. The extent to which an adverse environment can accelerate LEE has been grossly unreported in current literature to date. The dynamic modelling approach appeared to be capable of monitoring the onset and severity of rain leading edge erosion with the caveat that further testing be conducted beyond two years of operation. This study also revealed the inadequacy of current leading edge protection coating testing standards. The Springer method of correlating rain erosion test results to actual field performance failed dramatically, most likely due to the incongruency between testing and field conditions. Furthermore, rain erosion testing does not account for erosion by solid airborne particles, which has been shown to greatly accelerate leading edge erosion. Therefore, it is imperative that a new testing standard is developed for leading edge protection coatings that accounts for erosion by solid airborne particles and facilitates greater correlation between test results and field performance.

The quantification of energy losses associated with leading edge erosion revealed that an average AEP loss of 1.8% was found on a site with medium levels of leading edge erosion, with the worst affected turbine experiencing losses of 4.9%. While these results were largely congruent with the literature consensus, further such analysis using LIDAR technologies or individual met masts must be conducted to establish greater knowledge of the associated AEP losses with actual field turbines. This will be vital in enabling developers to compute more accurate financial forecasts of the lifetime performance of their site, particularly in an era of declining subsidies.

Acknowledgements

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